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Numerical study of the behaviour of a surface fire propagating through a firebreak built in a Mediterranean shrub layer

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ABSTRACT

The efficiency of a firebreak, built in a shrubland has been studied numerically using a multiphase physical model. The physical mechanisms governing the propagation of the surface fire and the consequences upon the temperature signal and the radiative heat flux received by a target located at 1 m above the ground level, have been firstly studied before positioning the firebreak. The role played by the flame and the recirculation of hot gases to the ignition of unburned fuel (especially the dry grass) ahead of the fire front have been clearly identified. Four values of the firebreak width L_C (ranged between 5 and 20 m) and 3 values of wind velocities (ranged between 1 and 8 m/s) have been tested. The simulations show that above a threshold value of this parameter, even if a small amount of the fuel located on the opposite side of the firebreak was ignited, the released energy was not sufficient to sustain the propagation of the surface fire after crossing the firebreak.

1. Introduction

In response to the massive wildfires which have affected US from 1870 to 1920 (Peshtigo in 1871, Hinckley in 1894, Big Blowup in 1910, Cloquet in 1918 …), a new fire control policy, based on fire exclusion, was promoted for the next four decades in US and also in many other countries around the world [1,2]. The first consequence of this policy, often named “fire exclusion paradigm”, was to reduce the average surface area burned each year from 16–20 million hectares in 1930s to 2 million hectares in 1970s (this data concerns only the US). In a more recent period, new worse consequences were appeared, resulting from the transformation of some ecosystems with the great accumulation of biomass and the extension of areas affected by high intensity fires. At the same time, the population migrations, from rural to urban zones, and the resulting exponential growth of cities, have promoted the extension of wildland urban interfaces (WUI). In a review paper, Hammer et al. [3] have shown that these two factors can explain the significant increase of destruction of structures (around +110% in California in comparing the periods 1955–1985 and 1985–2000) and deaths resulting from wildfires. In addition to this, it is well established now that global warming will affect fire regimes, with the risk to increase the occurrence of wildfires in regions until now not too much affected by this natural hazard [4]. The increase in fire fighting means cannot be considered as a sufficient and unique answer to this problem. Under the influence of fire ecological studies published in 1960s and 1970s, in which the role played by wildland fires has been recognised, for the regulation of the biomass [5], new practices have been reintroduced in forests in order to attenuate the consequences of the “fire exclusion paradigm”. This new policy consisted in reintroducing small intensity fires (prescribed burning, counter fires) in all ecosystems where this was possible. Other actions have been done to prevent the risk in the wildland urban interfaces (WUI) and in national and regional parks, in landscaping fuel breaks for example. The use of fire as a tool to reduce the biomass (prescribed burning) or to fight wildfires (back fires, tactical fires), needs to build a safety zone (a fuel break or a firebreak), where all or part of surface fuel was removed [6]. In order to secure a zone before igniting a back fire, the fuel must be removed on a band of few tens metres width (~30 m), in this case this safety zone is called a firebreak. In a WUI, as a function of the houses density, the same fuel treatment can be carried out at an individual level or for a houses cluster [7]. To protect a WUI or to reduce the spread of wildfires (more intense), this fuel discontinuity (named fuel break) must be at least 100 m width (some recent proposals recommend 400 m wide and in this case a part of the canopy can be kept, one calls this a shaded fuel break) [8]. To protect homes located in WUI, a clearing zone must be landscaped (the mandatory width in France varies between 50 and 100 m). Inside shaded fuel breaks, the reduction of fuel load must verified some specifications: for trees the distance between two crowns must be at least equal to 3 m and a *X* m tall shrub

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must be located at a distance from the projection of the crown on the ground at least equal to 2 times X, the distance between two shrubs must be at least equal to two times X if the slope is ranged between 0 and 20%, 4 times X for slope ranged between 21 and 40% and 6 times X for slope exceeding 40%. Some post-fires studies, have also underlined the danger represented by the ornamental vegetation located near houses [9]. Very few papers in the literature, have addressed the problem of the minimum width necessary to build a safe firebreak or a fuel break. Emmons was one of the firsts to propose a physical model for dimensioning the minimum width to build a safe firebreak [10]. This 1D model was based on the assumption that the heat transfer between the fire front and the vegetation was governed exclusively by radiation. From an energy balance equation, he had proposed (for a homogeneous vegetation layer) that the width of a firebreak (L_C) must verify a criterion, as a function of the Leaf Area Index (LAI) characterizing the vegetation layer and the depth of the fire front (D_{Fire}) representing the behaviour and the history of the fire front:

$$L_C \geq \frac{LAI \times D_{Fire}}{2} \quad (1)$$

We can notice that the fuel moisture content (FMC) does not appear in this formula. We will partially examine in this paper, the role played by the width of a safety zone (it can be both a fuel break or a firebreak), especially in the case where the fire was able to ignite the fuel located after the firebreak, without reaching the minimum energy required to sustain the propagation beyond this last one.

The problem of dimensioning a safe fuel break around houses, is directly correlated to the notion of home ignition zone (HIZ) [2]. As underlined in the reference book published by Drysdale [11], the classical ignition theory has shown that the ignition time of a heated target is inversely proportional to the heat flux (thermally thin material) or the square of the heat flux (thermally thick material). As a example, a wood panel (thermally thick) requires a minimum heat flux of 13 kW/m^2, before promoting a piloted ignition for any exposure time [11,12]. For a wildfire in propagation, the heat source is in movement and consequently the time of exposure of a potential target located in the heat affected zone of the fire front is necessarily finite. Typical values of this exposure time has been evaluated to 1 min and less during the experimental campaign carried out in boreal forest in Canada (the International Crown Fire Modelling Experiment, ICFME) [12]. With these values, a physical–theoretical model (more or less derived from the classical ignition theory for thermally thick fuel), allows to predict a radiation heat flux for ignition equal to 31 kW/m^2, which gave a minimum fire/target distance for ignition nearly equal to 30 m (assuming a flame front 20 m high and 50 m wide) [12–14]. A post-fire analysis on the origin of the destruction of houses and buildings due to bushfire occurred in the region of Canberra in January 2003 [15] has shown that 50% of the houses ignitions were from embers, 35% from embers and radiant heat, and only 10% from radiant heat alone. If ignition occurred and even if at the very beginning, the resulting fire is not very intense, the chance of survival of a house depends strongly of the possibilities for owners or firefighters to defend it: many studies have shown that 70% of destroyed homes were not defended. This remark justify why if direct attack coming from radiant heat is not the major cause of ignition of homes, it must be considered as a serious problem in regarding if the magnitude of heat flux just near a house can permit or not to people (more or less well protected) to stay on place and to defend the house. Consequently others thresholds of radiant heat flux must be considered to define a safety zone around a house located in the WUI, such as [11,16,17]:

- 1 kW/m^2 the maximum heat flux value for indefinite skin exposure.
- 2.3 kW/m^2 the limit for pain after 2 min of skin exposure.
- 7 kW/m^2 the maximum heat flux tolerable by firefighters (with adequate protections).
- 10.4 kW/m^2 the limit for pain after 3 s of skin exposure.
- 16 kW/m^2 the limit for a second-degree burn after 5 s of skin exposure.

As indicated previously, ornamental vegetation constitutes also a source of vulnerability when it is located inside the immediate

Table 1
Physical properties of the solid fuel layer (B: bottom, I: inside, T: top) (data measured on the field on calcareous soil, Marseille area).

Species	Leaves	Fine Twigs	Twigs	Grass
Solid fuel density (kg/m^3)	810	900	930	440
Volume fractionx10^3 B/I/T	0.7/1/2	0.6/0.5/1	0.7/1.5/1	1/1/1
Fuel moisture content (FMC) (%)	70	70	70	10
Surface area to volume ratio (m^{-1})	5920	2700	1000	20000
Fuel depth (m)	0.75	0.75	0.75	0.25

Fig. 1. Typical Mediterranean landscape on a calcareous soil (garrigue).